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# Neutralino Production with Polarized Beams in Extended Supersymmetric Models*

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**Abstract**

We discuss associated neutralino production $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ with both beams polarized in the MSSM, NMSSM and an $\mathrm{E}_6$ model. It is shown that neutralinos with a large singlino component can be produced at a high luminosity linear collider in a broad parameter range. Polarization effects in the extended models are compared over the whole parameter space where the lightest neutralino is mainly a singlino. We explain the complete different behavior of these models in some parameter regions, which may help to identify the respective supersymmetric model.

# 1 Introduction

A linear collider with both beams polarized will be an excellent tool not only to discover supersymmetric particles but also to determine the underlying SUSY model. Associated neutralino production $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ could be the first kinematically accessible process that may allow a discrimination between the Minimal Supersymmetric Standard Model (MSSM) and its nonminimal extensions. Polarization of both beams will clearly facilitate this challenging task.

An extensive analysis of polarization and spin effects in neutralino production and subsequent decay including the complete spin correlations in the MSSM has been performed in [1]. This study also includes extended SUSY models: the Next-to-Minimal Supersymmetric Standard Model (NMSSM) with an additional Higgs singlet superfield and an $\mathrm{E}_6$ inspired model with a Higgs singlet and a new $\mathrm{U}(1)'$ gauge boson. Significant differences between the MSSM and SUSY models with gauge singlets arise by the neutralino singlet components which do not couple to (scalar) fermions and standard gauge bosons. Within a special scenario, where the masses of the light neutralinos were fixed in the three SUSY models and the lightest neutralino had a large singlino component in the extended models, the cross sections for neutralino production at an $e^+e^-$ linear collider with polarized

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beams have been discussed in [2], and complete different polarization asymmetries have been found.

Now the study of the polarization effects is extended to a large region of the parameter space where the lightest neutralino is mainly a singlino. Comparing the longitudinally polarized cross sections we identify the parameter regions where polarization effects may help to specify nonminimal supersymmetric models. Of course for an exact determination of the SUSY parameters and discrimination between SUSY models a precise analysis also of the decay characteristics is indispensable. For a special scenario this was done in [2], the extension to the whole parameter space is planned.

In the following sections 2 and 3 we introduce the considered SUSY models and show the unpolarized cross section for the neutralino production. Crucial for the understanding of the polarization effects are the couplings of the left and right selectrons to the produced neutralinos that will be discussed in section 4. A comprehensive comparison of the longitudinally polarized cross sections in the MSSM and the extended models in section 5 concludes our contribution.

# 2 Extended SUSY: NMSSM and $E_6$ model

We shortly present the parameters and the neutralino sectors of the supersymmetric models. In the MSSM the neutralino sector depends on the gaugino mass parameters $M_2$ and $M_1$, the higgsino mass parameter $\mu$ and the ratio of the Higgs vacuum expectation values $\tan\beta = v_2/v_1$. In this paper we assume the GUT-relation $M_1/M_2 = 5/3\tan^2\theta_W$ and scan over the $M$-$\mu$ plane with fixed $\tan\beta = 3$. The longitudinally polarized cross sections for neutralino production are compared with two extended SUSY models.

The NMSSM is the simplest extension of the MSSM by a Higgs singlet field with vacuum expectation value $x$ and hypercharge 0 [3]. The masses and couplings of the five neutralinos depend on $M_2$, $M_1$, $\tan\beta$, $x$ and the trilinear couplings $\lambda$ and $\kappa$ in the superpotential. Within the NMSSM, a light singlino-like neutralino cannot be experimentally excluded by LEP [4]. In order to obtain a light singlino-like neutralino $\tilde{\chi}^0_1$ we choose in the following $x = 1000$ GeV and $\kappa = 0.01$. Then nearly independently of the other parameters the $\tilde{\chi}^0_1$ has singlino character and a mass between about 9 and 28 GeV while the masses and mixings of the heavier neutralinos correspond to the MSSM with $\mu = \lambda x$.

Models with additional U(1) factors in the gauge group are a further extension of the MSSM beyond the NMSSM. They can be motivated by superstring theory [5] and imply an $E_6$ group as effective GUT group, which is broken to an effective low energy gauge group of rank 5 with one additional $U(1)'$ factor. This $E_6$ model contains one new gauge boson $Z'$ and an extended Higgs sector with one singlet superfield with vacuum expectation value $x$ as in the NMSSM [6]. To respect the experimental mass bounds of new gauge bosons [7] the vacuum expectation value of the singlet must be larger than 1 TeV.

The extended neutralino sector in the $E_6$ model contains six neutralinos, one $\tilde{Z}'$ gaugino and one singlino $\tilde{N}$ in addition to the MSSM [6, 8]. The $6\times 6$ neutralino mass matrix depends on six parameters: the $SU(2)_L$, $U(1)_Y$ and $U(1)'$ gaugino mass parameters $M_2$, $M_1$ and $M'$, $\tan\beta$, $x$ and the trilinear coupling $\lambda$ in the superpotential. With the GUT relation $M' = M_1$ between the U(1) gaugino mass parameters the four lighter neutralinos always have MSSM-like character if the MSSM parameter $\mu$ is identified with $\lambda x$

[9, 10], and the two heaviest neutralinos have large $\tilde{Z}'$ and $\tilde{N}$ components. Assuming $|M'| \gg x, M_1$, however, the lightest neutralino can be a nearly pure singlino [11]. Then $\tilde{\chi}^0_2, \ldots, \tilde{\chi}^0_5$ have MSSM-like character and the $\tilde{\chi}^0_6 \approx \tilde{Z}'$ has a mass $\mathcal{O}(M')$. Such scenarios where the spectrum of the lighter neutralinos is similar to the NMSSM will be discussed in the following.

Table 1 gives an overview over the described fixed parameters, while the remaining parameters $M_2$ and $\mu$ (or $\lambda x$) were scanned in the region $0 \leq M_2 \leq 500$ GeV, $-500 \leq \mu\ (\lambda x) \leq 500$ GeV observing the experimental bounds from the unsuccessful chargino and neutralino search at LEP2 [12]. Also shown are the masses and singlino components of the lightest neutralino in the extended models which do not extensively vary over the scanned parameter region. The selectron masses $m_{\tilde{e}_L} = 176$ GeV and $m_{\tilde{e}_R} = 132$ GeV are motivated by the DESY/ECFA reference scenario [13] and are fixed in all three models, for comparison.

| Model | $M'$/TeV | $x$/TeV | $\kappa$ | $\tan\beta$ | $m_{\tilde{\chi}^0_1}$/GeV | $\lvert\langle\chi^0_1\lvert\Psi_N\rangle\rvert^2$ |
|---|---|---|---|---|---|---|
| MSSM | — | — | — | 3 | 49.3 – 249.4 | 0 |
| NMSSM | — | 1 | 0.01 | 3 | 8.7 – 27.8 | 0.905 – 0.971 |
| $E_6$ | −50 | 3 | — | 3 | 30.5 – 32.9 | 0.979 – 0.996 |
| $E_6$ | +50 | 3 | — | 3 | 30.9 – 33.1 | 0.994 – 0.997 |
| $E_6$ | +35 | 3 | — | 3 | 44.6 – 46.7 | 0.994 – 0.996 |

Table 1: Parameters of the supersymmetric models. In the extended models the $\tilde{\chi}^0_1$ has dominant singlino component $\langle\chi^0_1|\Psi_N\rangle$ in the whole $M_2$-$\lambda x$ parameter space. The selectron masses $m_{\tilde{e}_L} = 176$ GeV and $m_{\tilde{e}_R} = 132$ GeV are fixed in all models.

# 3 Unpolarized cross sections

In this section we address the question if a neutralino with a dominant singlino component can be directly produced with a sufficient cross section at a linear collider.

The neutralino production cross section in the MSSM is well known [14]. Fig. 1(a) shows the contour lines for the unpolarized cross section $\sigma^{(00)}$ of $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ at a c.m.s. energy $\sqrt{s} = 500$ GeV in the $M_2$-$\mu$ parameter space. Depending on the masses and mixing characters of the light neutralinos it takes values up to 200 fb over most of the parameter space. Note the discontinuities (bold lines) for both positive and negative $\mu$ where $m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^0_3}$ and therefore the mixing character of $\tilde{\chi}^0_2$ changes [15].

In the NMSSM with a light singlino-dominated neutralino $\tilde{\chi}^0_1$ the unpolarized cross section (Fig. 2(a)) is significantly smaller since the singlino component does not couple to the $Z$ boson and the selectrons. It is only the small contribution from the other components of $\tilde{\chi}^0_1$ that accounts for the cross section. Nevertheless one gets even for a neutralino with a singlino component larger than 90 % production cross sections up to 30 fb which are expected to be clearly visible at a high luminosity linear collider ($\int \mathcal{L} = 500$/fb) [16]. The use of polarized beams can still enhance these cross sections as we discuss in the following sections.

In the E$_6$ model we explicitly study the dependence of the unpolarized cross sections on the parameter $M'$ in Figs. 3(a) – 5(a). For the large negative value $M' = -50$ TeV (Fig. 3(a)) the masses and the mixings of the light neutralinos are similar as in the NMSSM. Therefore one also obtains similar cross sections up to 9 fb. For positive $M'$ (Figs. 4(a), 5(a)), however, the singlino component is larger than 99.4 % in the whole parameter space. Thus the cross sections are reduced to maximum values of about 0.2 fb for $\lambda x < 0$ and 0.5 fb for $\lambda x > 0$ leading to at least 100 respective 250 events at the expected high luminosity linear collider.

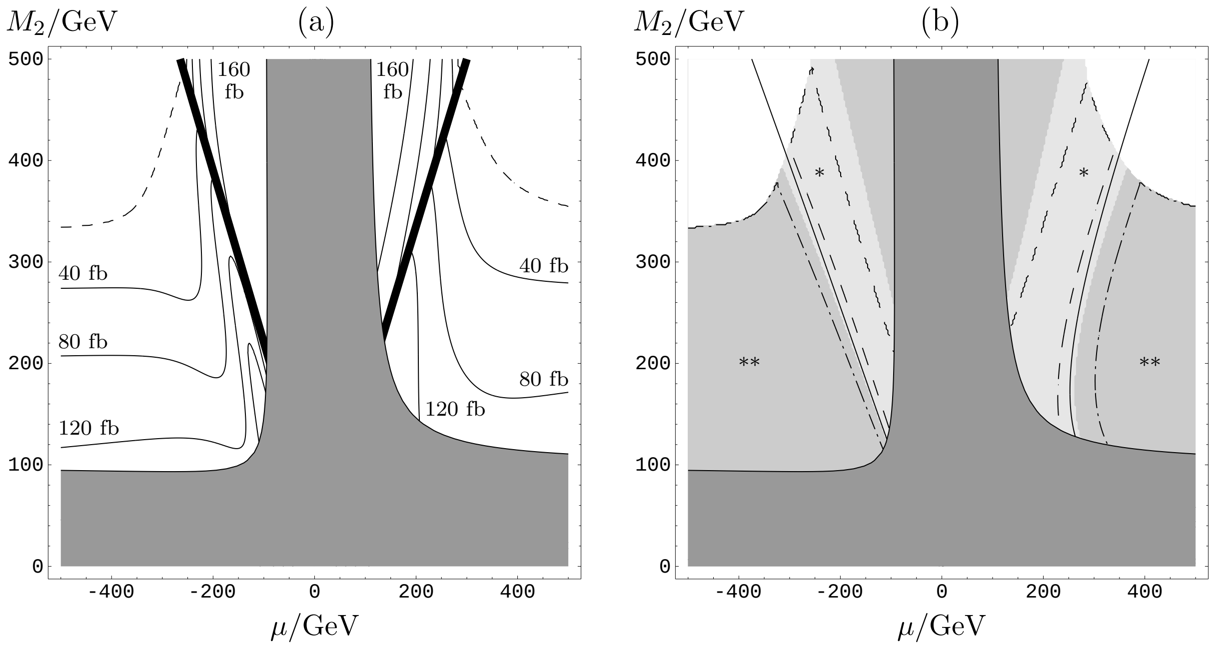


Figure 1: (a) Contour lines of the cross section of $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ for unpolarized beams in the MSSM for $\sqrt{s} = 500$ GeV and $\tan\beta = 3$. (b) Areas where the cross section $\sigma^{(+-)}$ (right handed polarized electrons and left handed polarized positrons, bright shaded) or $\sigma^{(-+)}$ (left handed polarized electrons and right handed polarized positrons, gray shaded) is largest, respectively. In the regions $*$ ($**$) within the dashed (dashed dotted) lines the ratio $\sigma^{(+-)}/\sigma^{(00)}$ ($\sigma^{(-+)}/\sigma^{(00)}$) is larger than 2 for $P^- = +0.85$, $P^+ = -0.6$ ($P^- = -0.85$, $P^+ = +0.6$). The solid line shows the contour $(f^R_{e1} f^R_{e2})^2/(f^L_{e1} f^L_{e2})^2 = 1$. The dark region marks the parameter space excluded by LEP2.

# 4 Neutralino couplings to selectrons and electrons

If apart from the singlino component which does not contribute to the production process both produced neutralinos $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ have dominant gaugino components, the contribution of $Z$ exchange can be neglected for energies above the $Z$ peak. Then for longitudinally polarized beams the cross section consists of two terms describing the exchange of left and right selectrons $\sigma = \sigma_{\tilde{e}_L} + \sigma_{\tilde{e}_R}$. The structure of $\sigma_{\tilde{e}_{L/R}}$ is [10]

$$\sigma_{\tilde{e}_{L/R}} = (f^{L/R}_{e1} f^{L/R}_{e2})^2 \left[(1 - P^-P^+) \mp (P^- - P^+)\right] \tilde{\sigma}(s, m_{\tilde{e}_{L/R}}, m_{\tilde{\chi}^0_{1/2}}) \tag{1}$$

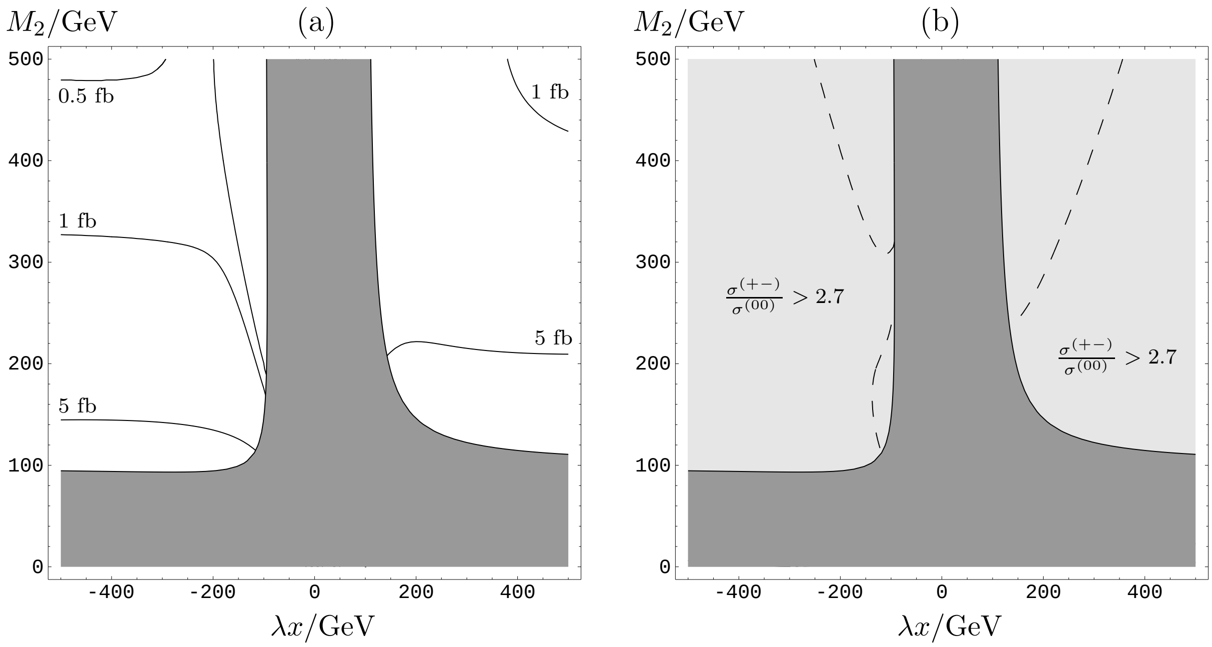


Figure 2: (a) Contour lines of the cross section of $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ for unpolarized beams in the NMSSM with $\kappa = 0.01$ for $\sqrt{s} = 500$ GeV and $\tan\beta = 3$. (b) In the whole parameter space $\sigma^{(+-)}$ (right handed polarized electrons and left handed polarized positrons, bright shaded) is largest. The dashed lines denote the contours $\sigma^{(+-)}/\sigma^{(00)} = 2.7$ for $P^- = +0.85$, $P^+ = -0.6$. The dark region marks the parameter space excluded by LEP2.

where $P^-$ and $P^+$ are the longitudinal polarizations of the electron and positron beam, respectively, and $\tilde{\sigma}$ is a function of the beam energy and the particle masses. For selectron masses of the same order of magnitude $m_{\tilde{e}_L} \approx m_{\tilde{e}_R}$ the polarization behavior is significantly determined by the ratio

$$r_f = \frac{(f^R_{e1} f^R_{e2})^2}{(f^L_{e1} f^L_{e2})^2} \tag{2}$$

of the couplings of the produced neutralinos to the left handed and right handed electrons and selectrons $f^{L/R}_{ei}$ [10, 17]. The effects of different masses, especially the extreme cases $m_{\tilde{e}_L} \ll (\gg)\, m_{\tilde{e}_R}$, are shortly mentioned in the following section.

In this contribution we consider longitudinal beam polarizations of $P^- = \pm 0.85$ for electrons and $P^+ = \pm 0.6$ for positrons [18]. The solid lines in Figs. 1(b), 4(b) and 5(b) show the contour for $r_f = 1$. In the NMSSM and the $E_6$ model with negative $M'$ (Figs. 2(b) and 3(b)) it is always $r_f > 1$. This contour line clearly separates the gray shaded regions with maximum cross sections for polarization configurations $(+-)$ (right handed polarized electrons and left handed polarized positrons) or $(-+)$ (vice versa) in the MSSM (Fig. 1(b)) in the gaugino region ($M_2 \lesssim 2|\mu|$). In the $E_6$ model (Figs. 4(b) and 5(b)) the situation is more complicated because the higgsino components of the $\tilde{\chi}_1^0$ are larger than the gaugino components in the whole parameter space. Nevertheless the contour $r_f = 1$ approximately describes the polarization behavior. The polarization effects in detail are discussed in the following section.

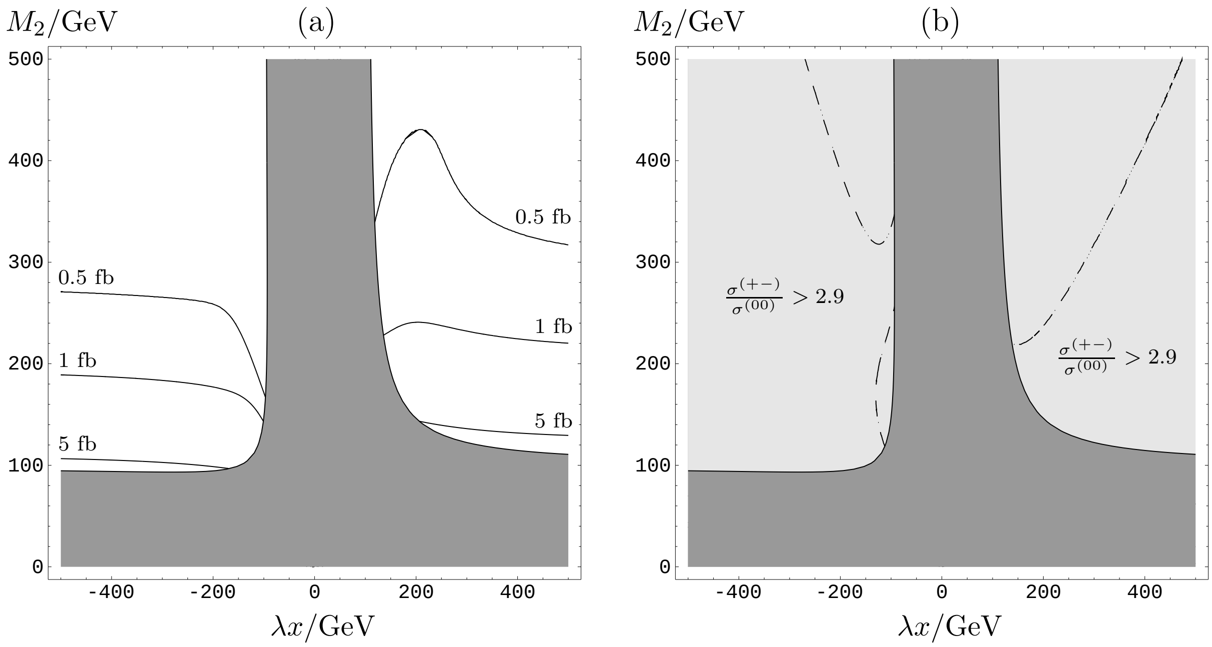


Figure 3: (a) Contour lines of the cross section of $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ for unpolarized beams in the E$_6$ model with $M' = -50$ TeV for $\sqrt{s} = 500$ GeV and $\tan\beta = 3$. (b) In the whole parameter space $\sigma^{(+-)}$ (right handed polarized electrons and left handed polarized positrons, bright shaded) is largest. The dashed lines denote the contours $\sigma^{(+-)}/\sigma^{(00)} = 2.9$ for $P^- = +0.85$, $P^+ = -0.6$. The dark region marks the parameter space excluded by LEP2.

# 5 Polarized cross sections

We compare the longitudinally polarized cross sections $\sigma^{(+-)}$ and $\sigma^{(-+)}$ where $(+-)$ and $(-+)$ denotes the polarization configuration ($P^- = +0.85, P^+ = -0.6$) and ($P^- = -0.85, P^+ = +0.6$), respectively. These polarization asymmetries may help to distinguish between the SUSY models. Figs. 1(b) – 5(b) present the regions where the different polarizations $(+-)$ or $(-+)$ lead to maximum cross sections. Polarization configurations with both beams polarized in the same direction or only one beam polarized are always smaller.

The following remarks apply to all models: If the gaugino-character of $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ is not too small (which is the case in the MSSM for $M_2 \lesssim 2|\mu|$) $\sigma^{(-+)}$ dominates if the gaugino-coupling of the left selectron is larger than that of the right one, $r_f < 1$, and the mass difference between the selectrons is rather small. Analogously for $r_f > 1$, $\sigma^{(+-)}$ turns out to be the dominating cross section.

This situation may change for other selectron masses. If $m_{\tilde{e}_L} \gg (\ll)\, m_{\tilde{e}_R}$ the exchange of the left (right) selectron in the neutralino production is strongly suppressed and $\sigma^{(+-)}$ ($\sigma^{(-+)}$) dominates in the whole gaugino region, cf. [19].

If the gaugino components of the produced neutralinos can be neglected, the ratio of the neutralino-selectron-electron couplings plays no role and the asymmetry in the MSSM and NMSSM

$$\frac{\sigma^{(-+)} - \sigma^{(+-)}}{\sigma^{(-+)} + \sigma^{(+-)}} \approx \frac{|P^-| + |P^+|}{1 + |P^-||P^+|}\,\frac{L^2 - R^2}{L^2 + R^2} > 0 \qquad (3)$$

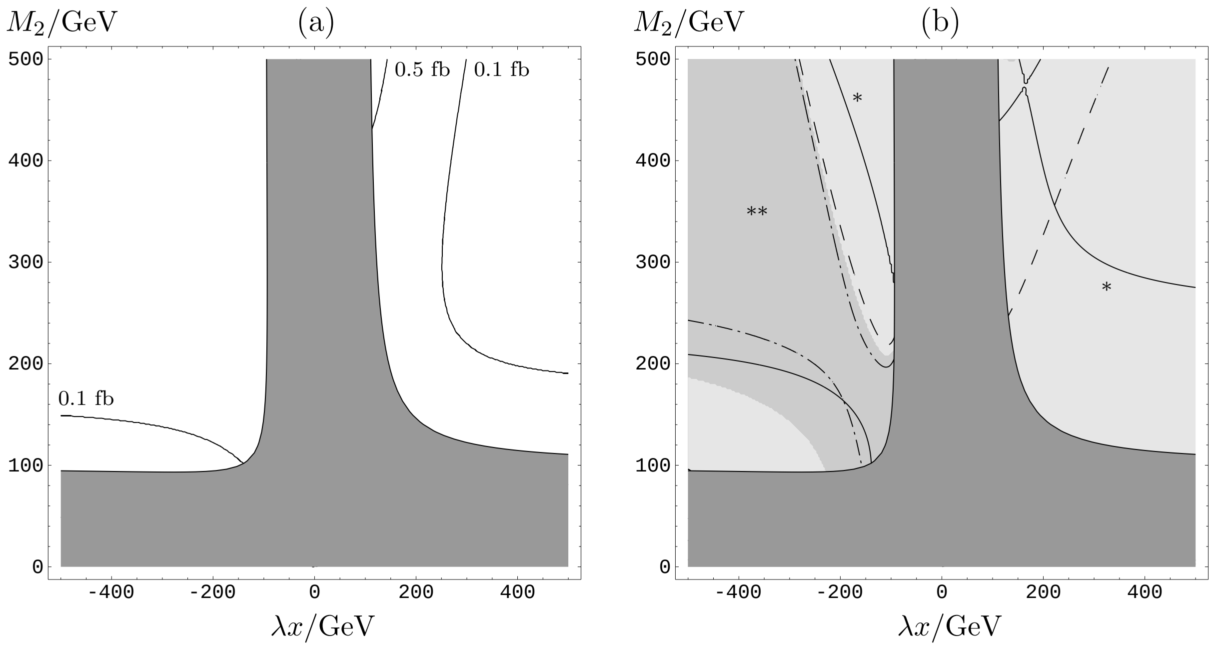


Figure 4: (a) Contour lines of the cross section of $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ for unpolarized beams in the $E_6$ model with $M' = +50$ TeV for $\sqrt{s} = 500$ GeV and $\tan\beta = 3$. (b) Areas where the cross section $\sigma^{(+-)}$ (right handed polarized electrons and left handed polarized positrons, bright shaded) or $\sigma^{(-+)}$ (left handed polarized electrons and right handed polarized positrons, gray shaded) is largest, respectively. In the regions $*$ ($**$) within the dashed (dashed dotted) lines the ratio $\sigma^{(+-)}/\sigma^{(00)}$ ($\sigma^{(-+)}/\sigma^{(00)}$) is larger than 2 for $P^- = +0.85$, $P^+ = -0.6$ ($P^- = -0.85$, $P^+ = +0.6$). The solid line shows the contour $(f^R_{e1}f^R_{e2})^2/(f^L_{e1}f^L_{e2})^2 = 1$. The dark region marks the parameter space excluded by LEP2.

depends only on the electron-$Z$ couplings $L = -1/2 + \sin^2\theta_W$ and $R = \sin^2\theta_W$. So $\sigma^{(-+)}$ is generally largest in the MSSM higgsino region $M_2 \gtrsim 2|\mu|$, whereas in the NMSSM the gaugino components of $\tilde{\chi}_2^0$ always cause $\sigma^{(+-)} > \sigma^{(-+)}$ for $M_2 < 500$ GeV. In the $E_6$ model formula (3) becomes more complicated due to $Z'$ exchange.

Because of $r_f > 1$ in the NMSSM and in the $E_6$ model with $M' = -50$ TeV $\sigma^{(+-)}$ dominates in the whole parameter space. In the $E_6$ model with positive $M'$ both cases $r_f > 1$ and $r_f < 1$ occur. Thus $\sigma^{(+-)}$ as well as $\sigma^{(-+)}$ can be largest. The form of the respective parameter regions crucially depends on the value of $M'$ (compare Figs. 4(b) and 5(b)) and is only approximately given by the contours $r_f = 1$ because here the higgsino character of $\tilde{\chi}_1^0$ is always rather large.

In all models the cross sections for both beams polarized are more than two times larger than the unpolarized cross sections in a large fraction of the parameter space. To describe this fact we define the ratio

$$r^{(\pm\mp)} = \frac{\sigma^{(\pm\mp)}}{\sigma^{(00)}}\,. \tag{4}$$

In the MSSM for $M_2 \lesssim 2|\mu|$ (gaugino-region) one nearly always obtains $r^{(+-)} > 2$ or $r^{(-+)} > 2$ in the respective regions. In the NMSSM and the $E_6$ model with negative $M'$ it is always $r^{(+-)} > 2$ and even $r^{(+-)} > 2.7$ (NMSSM) or 2.9 ($E_6$ model) in a large fraction of parameter space. And also for positive $M'$ $r^{(+-)} > 2$ or $r^{(-+)} > 2$ holds in large parameter

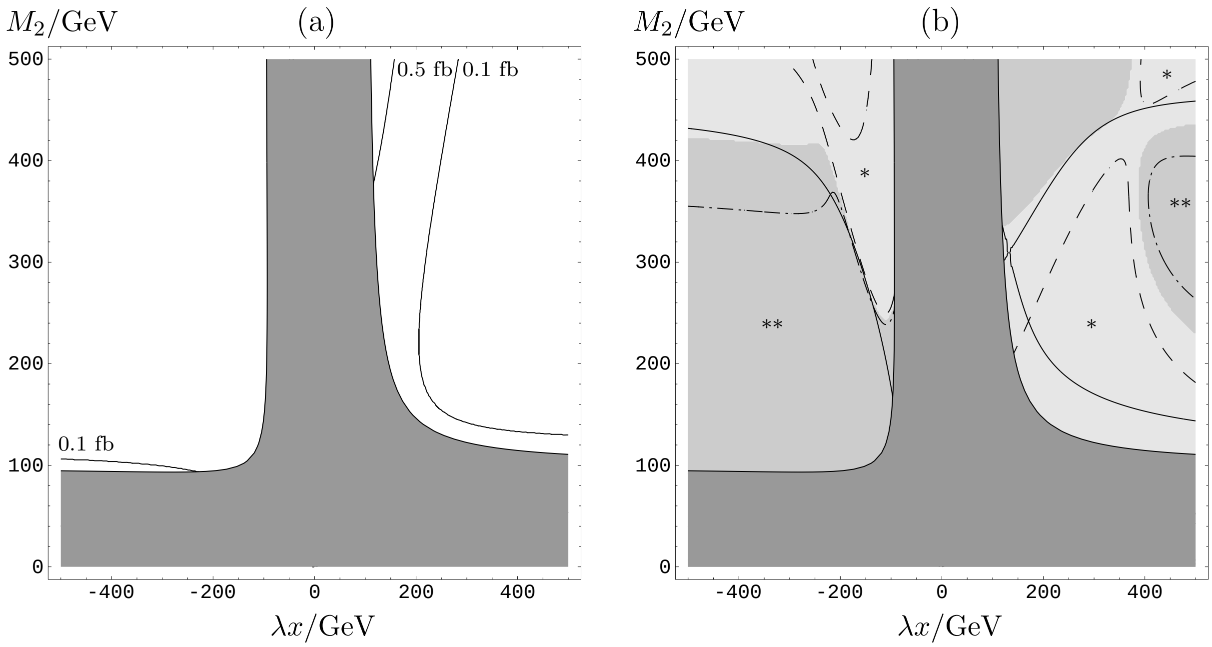


Figure 5: (a) Contour lines of the cross section of $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ for unpolarized beams in the $E_6$ model with $M' = +35$ TeV for $\sqrt{s} = 500$ GeV and $\tan\beta = 3$. (b) Areas where the cross section $\sigma^{(+-)}$ (right handed polarized electrons and left handed polarized positrons, bright shaded) or $\sigma^{(-+)}$ (left handed polarized electrons and right handed polarized positrons, gray shaded) is largest, respectively. In the regions $*$ ($**$) within the dashed (dashed dotted) lines the ratio $\sigma^{(+-)}/\sigma^{(00)}$ ($\sigma^{(-+)}/\sigma^{(00)}$) is larger than 2 for $P^- = +0.85$, $P^+ = -0.6$ ($P^- = -0.85$, $P^+ = +0.6$). The solid line shows the contour $(f^R_{e1}f^R_{e2})^2/(f^L_{e1}f^L_{e2})^2 = 1$. The dark region marks the parameter space excluded by LEP2.

regions. Thus polarization of both beams is an important tool to increase the event rates.

Finally we describe the parameter regions ($0 \le M_2 \le 500$ GeV, $-500$ GeV $\le \mu, \lambda x \le 500$ GeV) where significant differences between the SUSY models arise in neutralino production at a linear collider if both beams are polarized. In the extended models with a light singlino-like neutralino ($m_{\chi^0_1} \approx 30$ GeV) the polarization configuration $\sigma^{(+-)}$ dominates for $\lambda x > 0$, while in the MSSM $\sigma^{(-+)}$ is largest apart from a narrow band between $M_2 \approx \mu$ and $M_2 \approx 2\mu$. If the mass of the singlino-like neutralino, however, increases also the $E_6$ model with $M' = -35$ TeV allows $\sigma^{(-+)} > \sigma^{(+-)}$ in some parameter regions. In the MSSM, NMSSM and $E_6$ model with negative $M'$ the situation for $\mu$ or $\lambda x < 0$ is similar to $\mu, \lambda x > 0$. In the $E_6$ model with positive $M'$ the polarization asymmetries strongly depend on $M'$. For $M' = 50$ TeV with a lighter singlino $\sigma^{(+-)}$ dominates for $M_2 \ll -\lambda x$ and $M_2 \gg -\lambda x$ contrary to the MSSM, whereas for $M' = 35$ TeV $\sigma^{(+-)}$ dominates only for large $M_2$.

# 6 Conclusion

We summarize our results in two points:

- A high luminosity linear collider is sufficient for the direct production of neutralinos with dominant singlino components in extended supersymmetric models. Polariza-

tion of both beams is an important tool to increase the event rates by a factor of 2 or 3.

- The Minimal Supersymmetric Standard Model and extended supersymmetric models show a significant different polarization behavior for neutralino production in wide regions of the parameter space.

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